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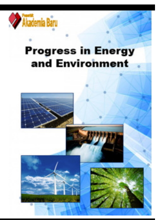
Journal homepage: : http://www.akademiabaru.com/progee.html
ISSN: 2600-7662



Improved Transfer Efficiency of Wireless Power Transmission System featuring Coil-Size Disparity

Research Article

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ARTICLE INFO

Article history:
Received 9 April 2017
Received in revised form 09 October 2017
Accepted 17 October 2017
Available online 26 October 2017

ABSTRACT

Wireless power transmission (WPT) is a hot topic today. However, researches on magnetic coupling resonant WPT system are mostly conducted on the system with equal coil size of the transmitter and receiver. Practically, coil size different condition will certainly exist due to the space constraint on the target receiving device. Researches being done on different coil size system were often reported with degraded performance. This work uses an impedance based quality factor tuning technique to design the WPT system to work with the system with coil size disparity. A prototype has proven to transfer the power wirelessly over a distance up 15cm with a near constant efficiency of 73%. The introduced method shows improved efficiency and it is comparable to those equal coil size systems.

Keywords:
Wireless power transmission, Different coil size system, Impedance matching, Transfer efficiency, Magnetic resonant coupling

1. Introduction

More and more consumer electronics such as smart phones, tablets and laptops are shrunk for portability. However, the battery technology is still far lagging behind to meet its energy consumption [1-2]. Limited battery capacity does result in frequent battery recharging or replacement. The charging process requires the device to be attached to a power cord, which ultimately hinders the device's mobility. Based on these and other factors, wireless power transmission (WPT) technology is gaining momentum for use in short to medium range power transfer applications [3-4].

WPT technology offers the promise to cut the last cable, which is the charging cord. It offers the advantages of neat, tidy and no-cable environment. Furthermore, with the removal of the charging cable, the devices can be completely mobile for the convenience of the users and eliminate the chance of getting electric shocks due to cable leakage [5]. The entire charging process is now completely autonomous when the device is residing in the charging hotspot and the appliances can now be assumed to have unlimited power.

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In order to meet this target, significant researches had been carried out on this topic. Since the introduction of the magnetic resonant coupling technique by the MIT researchers to transmit power wirelessly over a distance of about 2 meters with an efficiency of 40%, this technique had been researched extensively [6–8]. For example, various system analysis and modelling had been done [9-11]. Efficiency improvement by adjusting the numerous coils coupling to attain the matching condition was performed [12]. The WPT system was also designed to work at a reduced frequency to reduce the switching losses from in the circuits [13].

The magnetic resonant coupling technique is a non-radiative technique which is relatively safe to be implemented [5]. Its operation is built on the concept that the resonant objects are able to exchange energy effectively. Therefore, the WPT system is intended to work at specific resonant frequency [6]. The WPT system is basically consisting of at least one pair of coil to be used as the transmitter and receiver. The receiving coil is magnetically coupled to the transmitting coil. The changing of magnetic flux will eventually induce e.m.f. to drive the target device.

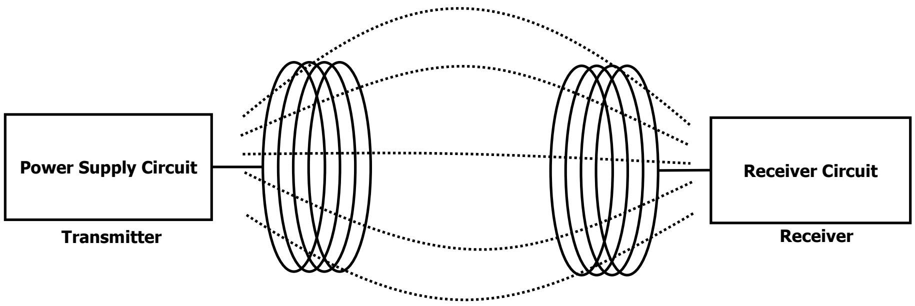

Fig. 1. An illustration of an equal coil size magnetic resonant coupling WPT system

Despite of good performance had been reported with this magnetic resonant coupling technique, most of the works were being conducted with identical coil size for both transmitter and receiver as depicted in **Fig. 1** [2, 14]. This does not reflect the actual working condition in most of the cases [15]. Due to the physical constraints in term of size and shapes of the target device, a realistic system will certainly have the size disparity between the transmitter and receiver [16]. For example, a smart phone can only install a receiver with a coil size not larger than 5 cm. Usually this receiver size will be much smaller as compared to the transmitter. The WPT system should aim to cater for this condition.

Often, different coil size system is reported to have a lower performance as compared to the system with equal coil size [17, 18]. For making the WPT technology to work with small consumer electronics, this work come with the design on impedance based quality factor tuning to improve the performance of the WPT system to work with different coil size condition. By properly adjusting the source and load impedance, the quality factor of the transmitting and receiving coil will be increased and therefore result in an improvement of the transfer efficiency.

2. Methodology

2.1 *Coil Size Disparity WPT System*

The block diagram of a typical coil size disparity magnetic resonant coupling WPT system is illustrated in **Fig. 2**. The power is converted from DC into high frequency AC to generate magnetic field around the transmitting coil. The magnetic field is subsequently coupled to the smaller receiving coil and induced an e.m.f. This receiving energy is then regulated to power up the load.

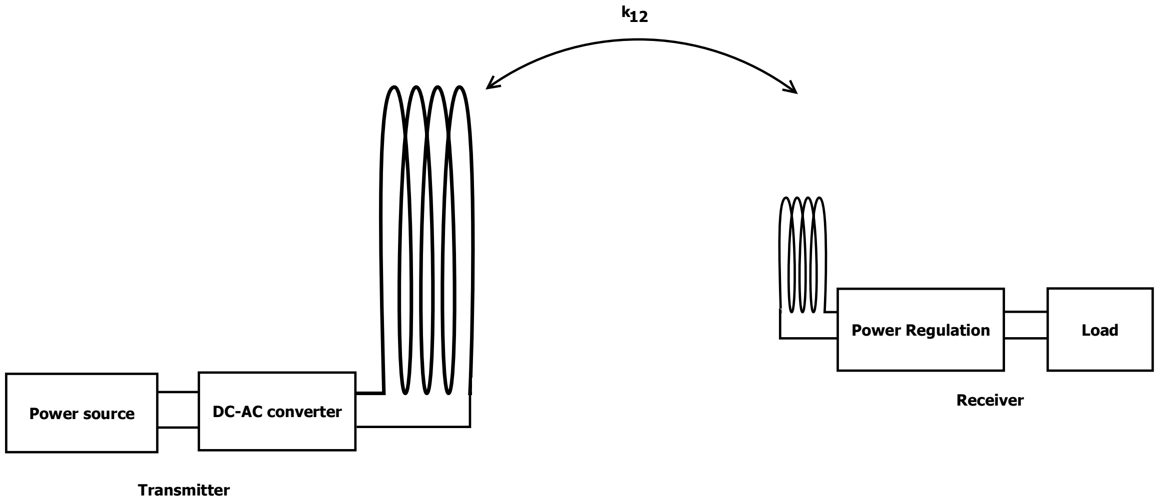

Fig. 2. A practical coil size disparity WPT system where the receiver coil size is much smaller as compared to the transmitter

The receiver size is usually smaller as compared to the transmitter due to the limited available space in the target device. The difference in coil size results in a low coupling between the coils, hence lower the power transfer efficiency. In this work, an impedance based quality factor tuning technique is carried on. An improved quality factor system can eventually compensate the effect of low coupling, hence lead to the improvement in the transfer efficiency on this coil size disparity WPT system.

2.2 *System Modelling*

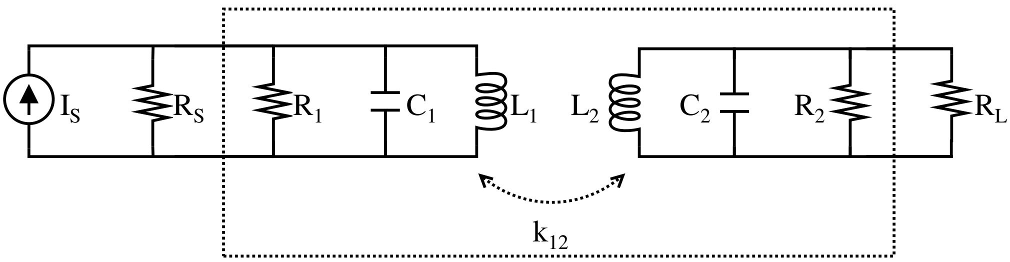

Fig. 3. Modelling of the WPT system in **Fig. 2**

The system in **Fig. 2** can be modelled as a parallel to parallel WPT system as depicted by **Fig. 3**. L_1 indicates the transmitting coil and L_2 is the receiving coil. Each coil is compensated by C_1 and C_2 respectively to form a LC tank circuit with the same operating frequency, f_r as indicated by equation (1). The coils are coupled together with coupling coefficient, k_{12} as shown by equation (2) whereby M_{12} is the mutual inductance of the transmitting and receiving coil. The R_1 and R_2 denote the internal losses contributed by the coil and compensating capacitor, for the transmitter and receiver respectively. R_s is the output impedance of the DC-AC converter and R_L is the target load.

The transfer efficiency of this system can be expressed by Eq. (3) where Q_1 and Q_2 is the loaded quality factor of the coil and they are being expressed in Eq. (4) and (5).

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

$$k_{12}=\frac{M_{12}}{\sqrt{L_1L_2}} \quad (2)$$

$$\eta_t=\frac{2k_{12}\sqrt{Q_1Q_2R_1R_2}}{\sqrt{\left[k_{12}^4(Q_1^2+1)(Q_2^2+1)+2k_{12}^2(Q_1Q_2\text{-}1)+1\right](R_S+R_1)(R_2+R_L)}} \quad (3)$$

$$Q_1=\frac{R_1\;//\;R_S}{\omega L_1} \quad (4)$$

$$Q_2=\frac{R_2\;//\;R_L}{\omega L_2} \quad (5)$$

Examining Eq. (3), the transfer efficiency is a function of the coil coupling and quality factors. A higher quality factor, Q can serve to mitigate the effect of the lowered coil coupling due to the coil size disparity. The quality factor is directly proportional to the equivalent impedance of the system as being displayed in Eq. (4) and (5). In this case, the equivalent impedance can be decreased by the loading effect of the R_S or R_L. Therefore, proper tuning of these impedances is a must for increasing the coil quality factor hence improve the transfer efficiency of a WPT system.

The R_S or R_L values can be set based on the impedance matching technique discussed in [19] so that they are equivalent to the input and output impedance of the system respectively. The formulae are seen from Eq. (6) and (7).

$$R_S=\frac{L_1R_1R_2}{2(L_1R_2+L_2R_1)} \quad (6)$$

$$R_L=\frac{L_2R_1R_2}{L_1R_2+L_2R_1} \quad (7)$$

Setting the R_S or R_L values to be equivalent to the input and output impedance of the system will increase the equivalent impedance of Eq. (4) and (5), hence contribute directly to the leverage of loaded quality factor Q_1 and Q_2. As a result, a higher transfer efficiency system can be achieved.

2.3 *Experiment Setup*

For verification, experiment was being conducted by using a transmitting coil with a diameter of 19 cm and a receiving coil with a diameter of 10 cm. These two coils were compensated with capacitors to work at 945 kHz resonant frequency. All the coil parameters were being recorded in **Table 1**.

Table 1 Coil parameters

Transmitter		Receiver	
Element	Value	Element	Value
L_1	4.507 µH	L_2	5.612 µH
C_1	6.216 nF	C_2	5.047 nF
R_1	3.432 kΩ	R_2	4.665 kΩ
Q_1	128	Q_2	140

The transfer efficiency was being indicated by the $|S_{21}|$ parameter measured by Rohde & Schwarz ZVB8 Vector Network Analyzer (VNA). Optimal R_S or R_L values were being computed according to Eq. (6) and (7). Since the characteristic impedance, R_o of the VNA is 50 Ω, a pair of L-match network was used to transform the impedance to the corresponding value as being listed in **Table 2**. The connections of the experimental setup are indicated by **Fig. 4**.

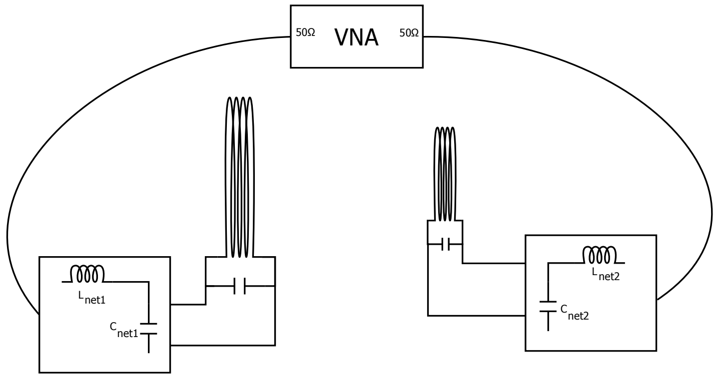

Fig. 4. Connections of experiment setup

The transmitter location was fixed and the receiver was gradually moved away from the transmitter along the axis. The transfer efficiency is being measured on every 1 cm, starting from 2 cm to 30 cm. For comparison, the same system without tuning was also measured. The constructed experimental setup is shown in **Fig. 5**.

Table 2 L-match network design

Transmitter		Receiver	
Element	Value	Element	Value
R_o	50 Ω	R_o	50 Ω
R_S	896 Ω	R_L	2230 Ω
L_{net1}	34.5 μH	L_{net2}	55.4 μH
C_{net1}	771 pF	C_{net2}	497 pF

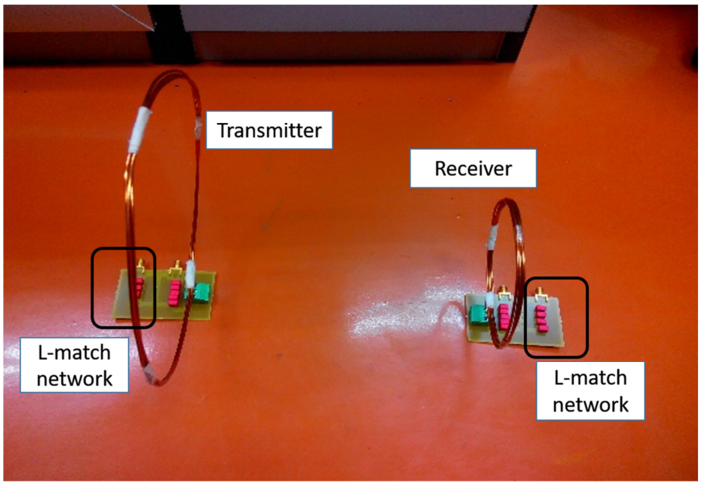

Fig. 5. Experiment setup for different coil size WPT system

For consistency, the experiment result was being verified by computer simulation using the Agilent Advanced Design System (ADS).

3. Results and Discussion

The result of transfer efficiency vs distance with and without the proposed tuning technique is demonstrated by **Fig. 6** and **Fig. 7**, respectively. For the system with the proposed impedance based quality factor tuning technique, the initial transfer efficiency is about 73% at a distance of 2 cm and it is kept nearly constant with the increasing of transmission distance until 15 cm. After that, the transfer efficiency is now beginning to drop gradually. The distance of 15 cm is termed as critical coupling point. The system can no longer be able to drive a given load at maximum efficiency beyond this distance [7].

As opposed to the system without any tuning, the initial transfer efficiency is only about 55% at a distance of 2cm. It is degrading sharply with every incremental of transmission distance. The experimental results are following closely with the simulation results.

Apparently, there is an improvement in the transfer efficiency of the different coil size WPT system with the introduced tuning. The initial efficiency is 1.3 times better and at its maximum transmission distance, it is 7 times better as compared.

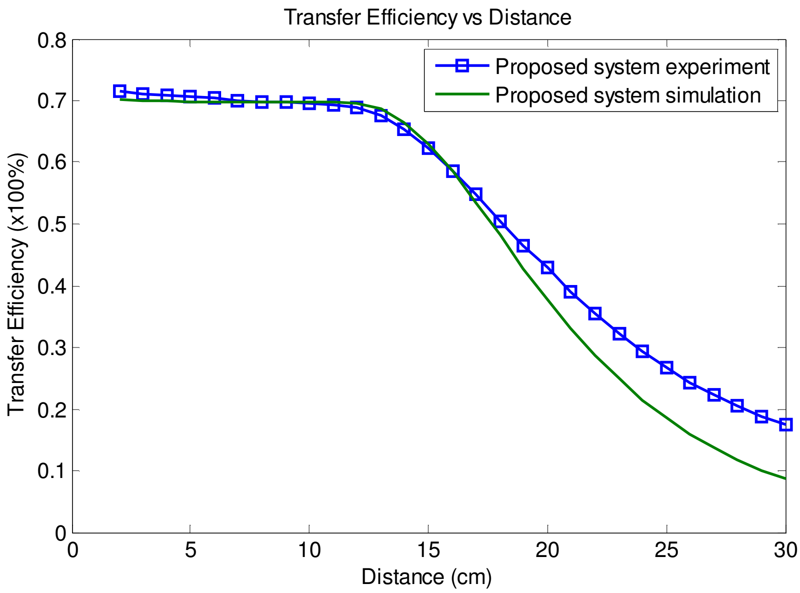

Fig. 6. Transfer efficiency for the different coil size WPT system with proposed impedance based quality factor tuning technique.

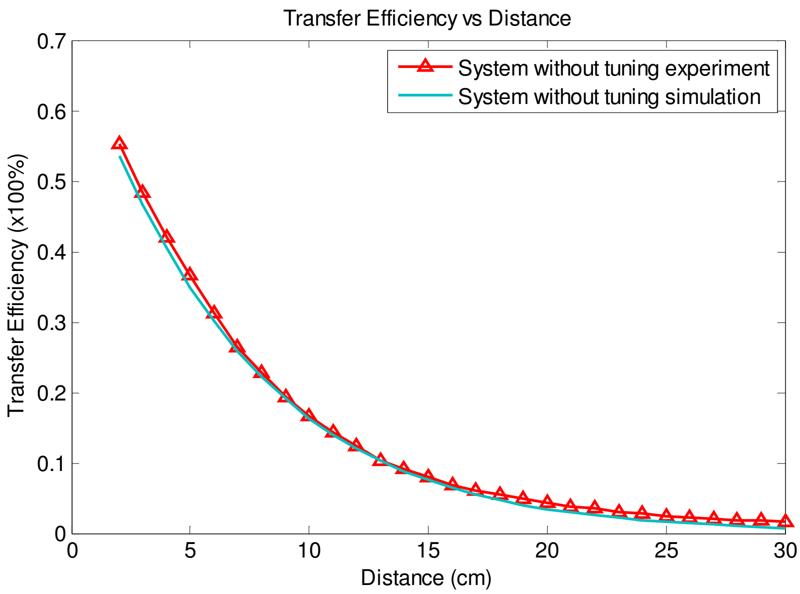

Fig. 7. Transfer efficiency for the different coil size WPT system without any tuning.

For benchmarking this system and having comparison with the other works, coil size is being normalized based on the transmitter and receiver coil size. The normalized coil diameter is being defined as $d_n=\sqrt{d_{tx} \cdot d_{rx}}$. Then, the ratio between the maximum transmission distance, D and the normalized coil diameter, d_n is being compared [20]. The greater D/d_n ratio means that the system is able to maintain its transfer efficiency over a longer transmission distance.

Table 3 Comparison with other works

Ref.	Tx (cm)	Rx (cm)	d_n (cm)	D (cm)	D/ d_n	η_t	Remark
[7]	59	59	59.0	70	1.19	70%	Equal coil size
[15]	3.8	1.8	2.6	1.5	0.57	85%	Different coil size
[21]	6.9	2	3.7	1	0.27	41.2% (1MHz) and 85.8% (5MHz)	Different coil size
[22]	35	20	26.5	20	0.76	80%	Different coil size
[23]	28.5	5.8	12.9	5	0.39	80%	Different coil size
This work	**19**	**10**	**13.8**	**15**	**1.09**	**73%**	Different coil size
[20]	10	10	10.0	10	1.00	85%	Equal coil size

Table 3 displays the comparison with related works. Four works with different coil size system [15, 21, 22, 23] and two with equal coil size system [7, 20] are being displayed. Based on the results, the proposed system was showing a great improvement by maintaining its efficiency over a transmission distance up to 1.19 times of its normalized coil diameter. The D/d_n ratio indicates that this work is surpassing all the different coil size WPT system by maintaining higher transfer efficiency over a longer distance. Not only that, it is likewise comparable to those equal coil size WPT system.

4. Conclusion

In conclusion, the performance for the different coil size WPT system had been enhanced with the introduction of impedance based quality factor tuning method. A 1.3 times improvements of transfer efficiency and 7 times longer transmission distances had been reported. The system performance is now analogous to those equal coil size systems. With this technique, the WPT system can now be more practical since the coil size different issue can no longer affect the system performance. It will be beneficial to those applications such as small electronic or medical implants.

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